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Estimation of local spawning biomass of Atlantic Herring from acoustic data collected during fall commercial gillnet fishing activities in the southern Gulf of St. Lawrence (NAFO Div. 4T)

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

In partnership with Fisheries and Oceans Canada (DFO), fish harvesters participating in the Atlantic herring (*Clupea harengus*) fall fishery in NAFO Div. 4T surveyed five spawning grounds in the southern Gulf of St. Lawrence using acoustic sounders over the course of their regular fishing activities from 2002 to 2012. Using a statistical method developed for Fisherman's Bank, seasonal biomass was estimated for all five spawning grounds. Acoustic data from each area was processed and analyzed to produce nightly biomass estimates for a subset of days over the season. Missing biomass values were simulated using a Bayesian time-series model, then grouped by spawning aggregation using a spatial-temporal clustering model. Seasonal biomass estimates were then produced by year and region. While this approach showed some promise, the model did not provide realistic results for two of the five regions. Furthermore, there are also underlying methodological and biological issues which raise significant doubts as to the comparability of results among regions. Given the inconsistencies in model performance and the underlying issues with the data it was decided that these data could not be used to develop a time series of local abundance indices for herring as part of the fall herring stock assessment. Recommendations are made to aid in future spawning bed specific acoustic surveys.

Estimation de la biomasse du stock de reproducteurs de harengs de l'Atlantique à l'échelle locale à partir des données acoustiques recueillies au cours des activités de pêche commerciale au filet maillant d'automne dans le sud du golfe du Saint-Laurent (division 4T de l'Organisation des pêches de l'Atlantique Nord-Ouest (OPANO))

RÉSUMÉ

En partenariat avec Pêches et Océans Canada (MPO), les pêcheurs participant à la pêche d'automne du hareng de l'Atlantique (*Clupea harengus*) dans la division 4T de l'OPANO ont effectué des relevés dans cinq frayères du sud du golfe du Saint-Laurent en utilisant des sondeurs acoustiques pendant leurs activités de pêche courantes entre 2002 et 2012. À l'aide d'une méthode statistique conçue pour le Fisherman's Bank, on a estimé la biomasse saisonnière pour les cinq lieux de frai. Des données acoustiques de chaque zone ont été traitées et analysées afin de produire des estimations de la biomasse chaque nuit pour un sous-ensemble de jours au cours de la saison. Les valeurs de la biomasse manquantes ont été simulées à l'aide d'un modèle bayésien d'ajustement des séries chronologiques puis classées par groupement de poissons en frai à l'aide d'un modèle de regroupement spatiotemporel. Les estimations de la biomasse saisonnière ont ensuite été produites par année et par région. Bien que cette méthode se soit révélée assez prometteuse, le modèle n'a pas fourni des résultats réalistes pour deux des cinq régions. De plus, il y a aussi des problèmes méthodologiques et biologiques sous-jacents qui soulèvent de sérieux doutes quant à la comparabilité des résultats entre les régions. Compte tenu des irrégularités dans le rendement du modèle et des problèmes sous-jacents liés aux données, il a été décidé que ces données ne pouvaient pas être utilisées pour élaborer une série chronologique d'indices de l'abondance locale du hareng dans le cadre de l'évaluation du stock de reproducteurs d'automne de hareng. Des recommandations sont formulées pour faciliter les relevés acoustiques propres aux frayères à venir.

INTRODUCTION

Population biomass and fishing mortality estimates are key components of fishery management decision frameworks, and are necessary for developing harvest control rules based on defined reference points (DFO 2006). The risk of not achieving sustainability objectives when fisheries occur on discrete spawning grounds increases when information is only obtained for large scale processes. Managing diverse herring spawning grounds for sustainability is important for conserving intraspecific biodiversity and adaptive potential (Sinclair 1988; Stephenson et al. 2001).

Until 2014, the stock assessment for the southern Gulf of St. Lawrence (sGSL) fall Atlantic herring (*Clupea harengus*) stock used a population model adjusted to annual gillnet catch-per-unit-effort (CPUE) from all spawning grounds combined and management provides Total Allowable Catch (TAC) advice based on the overall sGSL biomass (LeBlanc et al. 2015). There are concerns that gillnet CPUE does not track population biomass well, because fisheries that target spawning aggregations often exhibit hyperstability, where CPUEs remain elevated even as stock abundance declines (Erisman et al. 2011; Swain 2016).

Acoustic data from fishing vessels have been used to analyze school morphology characteristics, spatial patterns, relative changes in school density (Shen et al. 2008) and to develop estimates of abundance (Melvin et al. 2002; Honkalehto et al. 2011). Derivation of an annual seasonal index of biomass of herring from fishery acoustic data have been problematic for two reasons (Claytor and Clay 2001). First, the behaviour of herring gradually accumulating on spawning grounds prior to spawning, if not accounted for, can lead to multiple counts of the same fish which leads to over-estimation of biomass. Second, missing data created by weather, equipment malfunction, fishery closures, and other reasons create a source of uncertainty and potential biases in biomass and exploitation rate estimates.

From 2002 to 2012, acoustic data were collected from commercial gill netting vessels while fishing on the five major Atlantic herring fall spawning areas located within the coastal waters of the sGSL. The fall spawning areas were Miscou (NB), Escuminac and Richibucto (NB), Fisherman's Bank (PEI), West PEI, and Pictou (NS) (Fig. 1). Acoustic data were to be collected according to a protocol described in Claytor and Allard (2001) for the purpose of developing a time series of local abundance indices for herring as part of the fall herring stock assessment. The objectives of this research document were to analyze the collected acoustic data and determine whether they could be used to derive an index of local abundance. Nightly biomass estimates were derived following a defined protocol (Claytor and Clay 2001) and an analytical method (Surette et al. 2015) was applied to estimate spawning bed specific estimates of annual abundance and area-specific estimates of exploitation rates for five sGSL fall spawning grounds. This novel method was developed to account for some aspects of herring spawning behaviour and includes many sources of uncertainty in its final inferences.

METHODS

Atlantic herring from the sGSL are comprised of two spawning components, a spring spawning component and a fall spawning component (Scott and Scott 1988; Messieh 1988). Both spawning components have preferred spawning seasons and specific grounds. Herring show a high degree of fidelity to a specific spawning season and spawning ground once they have spawned (Wheeler and Winters 1984; McQuinn 1997; Brophy et al. 2006). Herring spawn in temporally discrete groups, separated by several days to weeks in a single spawning season (Ware and Tanasichuk 1989). Genetic and morphometric differences found in spawning herring were consistent with a replacement period of 6 days or less (McPherson et al. 2003). Fall

spawning occurs from mid-August to mid-October, at depths of 5 to 25 m (Messieh and MacDougall 1984). The fall spawning component is the focus of this study.

Fisherman's Bank has been the focus of numerous prior studies on herring spawning behaviour. In situ observations showed that a spawning event and the creation of the associated spawning bed took place over the course of a single day (Messieh 1988). Between 1985 and 1995 the number of spawning beds surveyed on Fisherman's Bank per season varied from a minimum of 1 to a maximum of 7, with few cases of simultaneous spawning events (Table 1). Spawning season length (i.e., between the first and last spawning event) varied from 6 to 29 days (Cairns et al. 1996).

Herring spawn in multiple waves during the course of the season. Incoming schools of herring create spawning aggregations over spawning beds, and may be joined by further schools accumulating over several days. Herring subsequently dissipate after spawning, as evidenced by the low frequency of spawned herring in fishery catches. To avoid double-counting of fish during the accumulation phase, observations need to be partitioned by spawning waves. The method previously applied to Fisherman's Bank (Surette et al. 2015) is applied in this study to the other four spawning areas surveyed.

OVERVIEW OF ANALYSIS

The goal of the analysis is to estimate the total fall spawning biomass from a set of nightly acoustic observations. Seasonal biomass requires a daily tally of all incoming or outgoing fish over spawning grounds for each region. The data presents two difficulties. Firstly, biomass estimates are only available for nights where the participating fish harvester was active. Secondly, spawning aggregations contain a mixture of fish which entered the grounds during the previous 24 hours and those from days prior.

The analysis proceeds in three steps. The first is to process and analyze the nightly acoustic data for each region in order to obtain a nightly biomass estimate. The method is described in Claytor and Clay (2001). The second step is to use a model to simulate values for nights with missing observations. The third step is to partition nightly biomass into distinct spawning waves using a spatial-temporal model. This step provides estimates of recruitment and escape biomasses which are then summed into a seasonal estimate. Uncertainty due to missing observations and clustering were incorporated in each step of the analysis.

ACOUSTIC DATA ANALYSIS

Two data sources were used in the following model: region-specific landings from the sGSL fall gillnet fishery and region-specific acoustic data from participating fishing vessels. Nightly landings were obtained from dockside monitoring data compiled and archived by the Department of Fisheries and Oceans Statistics Branch. The acoustic data was obtained from one or two fishing vessels per night from each spawning ground (Fig. 2). Acoustic calibration, data collection and processing, as well as the method for calculating nightly biomass, are described in Claytor and Clay (2001).

Nightly biomass model

Observations from each day of the spawning season are required for calculating the seasonal biomass. Missing observations occurred due to logistical problems (e.g., equipment failure, vessel electrical problems), weekend fishery closures, inclement weather or the fishery attaining its quota before the end of the spawning season. Missing nightly biomass values were inferred using a time-series model.

Let b_{ijk} be the nightly biomass estimate for day *i*, year *j* and region *k*. Zero values and positive values of b_{ijk} were modeled separately. Let $z_{ijk} \sim Bern(\pi_{jk})$ be a binary random variable indicating whether b_{ijk} is zero ($z_{ijk} = 1$) or one ($z_{ijk} = 0$). For each year and region, positive values of b_{ijk} are assumed to be log-normally distributed realisations from a first order autoregressive process (AR(1)):

$$\varepsilon_{ijk} \sim N(\phi_k \varepsilon_{i-1,jk},\ \sigma_\varepsilon^2)$$

$$\mu_{ijk} = \alpha_{jk} + \varepsilon_{ijk}$$

$$b_{ijk} \mid z_{ijk} = 0 \sim LN(\mu_{ijk}, \sigma^2)$$

where the log-linear annual means $\alpha_{jk} \sim N(\mu_\alpha, \sigma_\alpha^2)$ were given a hierarchical prior, with $\mu_\alpha \sim N(0, 10^4)$ and $\sigma_\alpha^2 \sim InvGam(10^{-4}, 10^{-4})$, the AR(1) process error was given a prior of $\sigma_\varepsilon^2 \sim InvGam(10^{-4}, 10^{-4})$, the AR(1) autocorrelation parameter a prior of $\phi_k \sim U(0, 1)$, the nightly observation error parameter was given a prior of $\sigma^2 \sim InvGam(10^{-4}, 10^{-4})$ and the prior probability of observing a zero was given a hierarchical prior of $\pi_{jk} \sim Beta(a, b)$ with $a \sim Exp(1)$ and $b \sim Exp(1)$. An error (CV = 0.15), based on empirical considerations (Claytor and Allard 2001) was added to each nightly biomass as a proxy for estimation error. If landings were reported for a given night, missing observations were assumed to be drawn from a truncated distribution and these were used to inform missing observations by serving as lower bound in a censored log-normal distribution. When landings exceeded nightly biomass estimates, the latter were treated as missing values. The above model differed slightly from the one presented in Surette et al. (2015) which made no provision for autocorrelation between observations and had no inter-regional hierarchical priors as it was applied to Fisherman's Bank region only. The OpenBUGS code for this model is found in Appendix A.

For the purposes of this study, the fishing season was defined as a period of 28 days starting at the opening date of the fishery. The sampling period by participating vessels covers the potential spawning period of herring for each spawning area. The seasonal distribution of acoustic data samples for each region is shown in Figure 2.

Spatial-temporal clustering model

The locations of nightly aggregations were calculated directly from acoustic density data, as a density-weighted average of GPS coordinates. These coordinates were used as inputs in a spatial-temporal clustering model, used for partitioning observed spawning aggregations by spawning wave. Under this model, a temporal sequence of spatially proximate aggregations would likely be grouped together as a single spawning wave, while those which are spatially distant would not. Such structural features in the data aid in probabilistically inferring the spawning wave with which missing observations are associated. The model formulation is as follows.

Let x_{ijk} and y_{ijk} represent the horizontal and vertical coordinates (in UTM projection, NAD83, zone 20, scaled to kilometers) of the aggregation locations for day *i* of the fishing season at year *j* within spawning region *k*. The coordinates were modeled as random walks with heterogeneous variances:

$$x_{ijk} = x_{i-1,jk} + \varepsilon_{ijk}^x, \text{ with } \varepsilon_{ijk}^x \sim \mathrm{N}(0, \sigma_{s_{ijk}}^2)$$

$$y_{ijk} = y_{i-1,jk} + \varepsilon_{ijk}^y, \text{ with } \varepsilon_{ijk}^y \sim \mathrm{N}(0, \sigma_{s_{ijk}}^2)$$

where ε^x_{ijk} and ε^y_{ijk} are independent normal random variables, each with two variance parameters $\sigma_0^2 < \sigma_1^2$ which were given uninformative priors of $\mathrm{InvGam}(10^{-4}, 10^{-4})$. The choice of variance parameter used is controlled by a binary random variable s_{ijk}, modeled as a 2-state Markov chain s_{ijk}. Formally,

$$s_{ijk}|s_{i-1,jk} = 0 \sim \mathrm{Bern}(\pi_{0k})$$

$$s_{ijk}|s_{i-1,jk} = 1 \sim \mathrm{Bern}(\pi_{1k})$$

where state 0 indicates that the aggregation location from day *i* belongs to the same spawning wave as that of previous day and state 1 indicates that it belongs to a new spawning wave. The transition probabilities were given hierarchical priors of $\pi_{0k} \sim \mathrm{Beta}(a_0, b_0)$ and $\pi_{1k} \sim \mathrm{Beta}(a_1, b_1)$ with $a_0 \sim \mathrm{Exp}(1)$, $a_1 \sim \mathrm{Exp}(1)$, $b_0 \sim \mathrm{Exp}(1)$ and $b_1 \sim \mathrm{Exp}(1)$. The probability parameter π_{0k} controls the residence time of sequences within spawning events while π_{1k} controls how often an aggregation will be remain within the current spawning event, given that a new spawning event has just occurred. The spawning event to which an observation from day *i*, year *j* and region *k* belongs, labelled c_{ijk}, is the cumulative sum of the corresponding elements of s_{ijk} over the season:

$$c_{ijk} = \sum_{m=1}^{i} s_{mjk} + 1$$

This model was nearly identical to that presented in Surette et al. (2015), except for the hyperpriors placed on the transition probabilities and variance parameters, to allow for some pooling of information across regions.

For both the nightly biomass and spatial clustering model, posterior samples were drawn via Monte Carlo Markov Chain (MCMC), with a burn-in sample of 5,000 iterations, plus a further draw of 100,000 samples which were thinned to one out of every twenty samples, for a total of 5,000 posterior samples. The OpenBUGS code (Lunn et al. 2000) for this model is found in Appendix B.

Seasonal biomass calculation

Simulations of nightly biomasses for each night of the season and their corresponding spawning wave identifications provided the input for calculating a seasonal spawning biomass. Each day of an event was assumed to be either a recruitment day, whereby a quantity of fish enter the aggregation, or an escape day, where fish exit the aggregation. For the first day of the event, biomass was considered to be recruitment. For subsequent days, recruitment and escape days were determined by comparing the biomass from day *i+1* (b_{i+1}) with the residual biomass of the day *i*, expressed as the difference of the biomass from day *i* (b_i) and the landings (l_i). If b_{i+1} was larger, it was interpreted as a recruitment day, otherwise it was an escape day. This recruitment was calculated as the difference between the biomass b_{i+1} and the residual biomass r_i. The seasonal biomass is defined as the sum of the recruitment biomasses.

A minimum sequence of three days was imposed for a simulated spawning event to be considered valid in the summation of seasonal spawning biomass. Sequences less than three days were ignored in the summation, and were considered as roaming fish not actively participating in a spawning event.

RESULTS

A log-scale scatterplot of landings versus estimated nightly biomass is shown in Figure 3. The correlation between the two values is weak; high biomass estimates do not imply high landings. Despite efforts to have good coverage of the spawning aggregation by the participating fish harvesters, 22% of nightly biomass estimates were less than the reported nightly landings. In the most severe cases, the biomass estimates were 10 to 50 times less than the landings. Estimates of biomass from the Miscou spawning area showed the largest discrepancies between biomass and landings.

The spatial distributions of spawning aggregations used in the spatial-temporal clustering model are shown in Figure 4 for each spawning region. Each region has its particular characteristics. Where Fisherman's Bank has clusters of locations strongly associated with a submerged ridge, Miscou has a more diffuse distribution across a large area. The distribution in Pictou is stretched out along the coast, and the fleet tends to move as schools of herring migrate through the region during the season. The distribution in the Escuminac region is composed of a northern and southern component. West PEI shows a more complex distribution of scattered locations and a small patch to the Northwest.

Summary statistics for the main model parameters are shown in Table 2.

For the nightly biomass model, credibility intervals showed that the auto-correlation parameter ϕ was not significant for Escuminac, Fisherman's Bank and West PEI, while it was marginally significant for Pictou and significant for Miscou. Variation in the biomass estimates was high and this was reflected in the posterior credibility intervals of missing observations. As an example, boxplots of posterior estimates for Miscou in 2006 are shown in Figure 5. The auto-correlation in the posterior simulations aided in the interpolation of missing values for Miscou. For other regions, the simulations for missing observations are nearly independent (i.e., their posterior means and variances are similar). Actual observations, shaded in grey, had the assumed baseline CV of 0.15.

For the spatial-temporal model, the error parameters σ_0 and σ_1 indicate the amount of distance change (in kilometers) between adjacent pairs of nightly spawning aggregations. Since the coordinates are modelled as a Gaussian random walk, the values of σ_0 and σ_1 are estimates which indicate that points along the walk will occur within σ_0 (intra-aggregation) and σ_1 (new aggregation) kilometers of the previous coordinate in 68% of cases. The intra-event distance parameter σ_0 was 0.53 km in Fisherman's Bank. In terms of surface area, this corresponds roughly to 0.88 km² at 68% areal coverage or 3.52 km² at 95% coverage, assuming a circular distribution of points. These values correspond well with spawning bed surface area estimates from previous studies (Table 1), which ranged from 0.36 km² to 1.44 km². We expect the spatial distribution of aggregations over and around spawning beds to be larger in extent than that of the spawning beds themselves. The σ_0 values for other regions were somewhat larger, from 0.68 km in West PEI to 1.46 km in Pictou. The extra-event distance parameter σ_1 showed more variability, going from 4.39 km in Fisherman's Bank to 24.0 km in Pictou. This parameter reflects the regional extent of coverage, with fish harvesters travelling significantly more during the season in some regions than in others.

The intra-event transition probability π_0 controls the residence time of aggregations within spawning events while the transition probability π_1 controls how often sequences of new spawning aggregations occur. Mean intra-event transition probabilities π_0 were generally high, from 0.81 for Fisherman's Bank, 0.87 for Escuminac and 0.88 for West PEI. The probability value for Miscou was exceptionally high at 0.97, while Pictou was very low with 0.55. The transition probabilities π_1 were more consistent between regions, ranging from 0.41 for Pictou to 0.65 in West PEI (Table 2).

The estimated number of spawning events for each spawning region by year is shown in Table 3. In general, the number of events was 3 or 4 events per 28-day period, the exception being Miscou, with generally one or two spawning events per period, owing to its high intra-event transition probability of 0.97.

Combining the nightly biomass and the spawning event inferences, seasonal biomass estimates for each region and year were obtained. Boxplots of seasonal estimates by spawning region by year are shown in Figure 6. Escuminac shows a downward trend in abundance during 2002 to 2010, with a slight increase in the last years. The estimates for Pictou fluctuate during the first half of the series and have increased in the past four years. Fisherman's Bank shows no overall trend but the last two years show low values with respect to the rest of the series. Estimates for West PEI are fairly stable, but show a slight decreasing trend across the series. Estimates for Miscou varied in the first half of the series, were low in 2008 and 2009, rose in 2010 and 2011, and then was reached a minimum in 2012. Given the variability in the inferred missing nightly biomasses (Fig. 5), the variability of the seasonal biomasses is correspondingly high. For comparison, the means of observed nightly biomass estimates, unadjusted for spawning events are shown in Figure 7. These trends are broadly similar to those of estimated seasonal biomasses.

The exploitation rate was calculated by dividing the total seasonal landings (for the same 28 day period as used in the model) by the seasonal biomass estimate. Boxplots of the exploitation rates by spawning area are presented in Figure 8. The scale of exploitation rates estimates varies among regions, with Escuminac and West PEI being somewhat lower than in other regions. Exploitation rate estimates in West PEI show an increasing trend. Escuminac, Fisherman's Bank, and Pictou show low rates for the last two years.

There are a number of caveats to consider in the interpretation of these results (both seasonal biomass and exploitation rates).

DISCUSSION

Science advice should be tailored to the management strategy. Currently, a reference removal rate is applied to a NAFO 4T Atlantic herring biomass estimate and a historical sharing formula is used to partition the TAC among the fleets from different regions. In this study, we evaluated the possibility of including spawning ground acoustic biomass indices as an additional element to the fall herring stock assessment and the subsequent science advice that could aid in partitioning the TAC. For the presented method to play such a role, seasonal biomass estimates must be comparable and be on the same scale among regions. How these estimates would actually be used to partition the TAC is beyond the scope of this review. We have thus restricted our discussion to the robustness of the science advice that could be provided using this model.

For seasonal biomass estimates to be valid and comparable across spawning areas, underlying assumptions of the model must be respected. The main assumptions are:

- nightly landings are accurate,
- nightly biomass estimates are unbiased estimators of true biomass in each spawning area,
- the models used are an adequate representation of the processes (e.g., spawning behaviour, fishing fleet dynamics, etc.) generating the observations and adequately account for double-counting, missing observations, and other potential sources of error,
- the study period captures the majority of spawning activity, and

- sampling methods and biological processes are sufficiently similar across regions that meaningful comparisons can be made.

For the fall herring fishery, there is little concern of bias in landings as there is 100% dockside monitoring, documented conversion factors, and controls on catch recording because nightly or weekly quotas are used to manage the fishery.

A working hypothesis for calculating the seasonal biomass is that nightly biomass estimates are on the same scale as landings. However, comparison of nightly biomass values with landings showed that these were underestimated in at least 22% of cases. These discrepancies were more prevalent in Miscou than in other regions. This percentage is probably higher given that nightly exploitation rates of 80% or larger are probably unreasonable in most regions.

Participating fish harvesters were to follow to a protocol for a complete fishery survey over each night of scanning, as defined in Claytor and Allard (2001). This protocol called for sampling vessels to collect acoustic data before and after a management-imposed nightly boat limit was caught. An incomplete survey was said to occur if the data collection was terminated when the boat limit was caught. If this protocol was properly adhered to, nightly biomass could be estimated from acoustic data before any fishing has occurred followed by a removal estimate after fishing activity has ceased. However, timing of data collection and discussions with fish harvesters indicated that acoustic scanning of spawning aggregations was generally performed during fishing activities, rather than before and after as the original protocol stated. Thus the data collection occurs as fish are actively being exploited, rather than in the pre- and post-fishing condition. Nightly biomass estimates were calculated using all validated acoustic data, irrespective of the time it was gathered or with reference to fleet fishing activities. Also, scanning during peak fishing activities is problematic because placement of gillnets over concentrations inhibits the ability of the sampling vessel to scan over the whole concentration. Thus the exploited spawning aggregation may be inadequately covered by the acoustic vessel, which may result in an underestimation of nightly biomass. In addition to possible bias in observed spawning aggregations, the presence of unobserved aggregations would also lead to underestimates of nightly biomass. This would be an issue where herring schools are more fragmented and spread out over spawning grounds. This would also have implications for fishing fleets which exploit them, in that these would also tend be more fragmented and widely distributed over spawning grounds. The sampling vessel in such cases would have had limited ability to cover the entire fleet activities. It is also possible that some spawning aggregations remain undetected by any portion of the fleet during a night of fishing in each region.

Biases could arise from the acoustic data itself, such as variability in backscattering in high target concentrations, the relationship between target strength and fish size, and acoustic extinction from near surface reverberation (Fréon and Misund 1999; Simmonds and MacLennan 2005; Brehmer et al. 2006; Boswell et al. 2008). Variability arising from these factors are minimized because the 28-day study period is relatively short, we are dealing with a single species in a well-defined phase of its life history (spawning) with a relatively restricted size-distribution, and the equipment is calibrated against objects of known target strength.

BIOMASS MODEL

The biomass model was developed as a way of inferring nightly biomass over the study period. However, there are two issues with the approach. The first is a potential sampling bias and the second is a lack of structure in the observations by which to make strong inferences.

The variability in nightly biomass estimates is very high with estimates ranging from 0 to over 33,000 tons. There was little evidence of temporal trends or autocorrelation in nightly biomass estimates making it difficult to infer missing biomass values. This may have some implications

with respect to the assumed process of accumulating waves of herring into spawning aggregations, in that residence times of herring within an aggregation may be relatively short, though uncertainties in the nightly biomass estimates as discussed above prohibit a strong conclusion.

Given that fishing is not independent of the quantity of fish, biases may arise through temporal sampling biases, given that sampling is not randomly distributed throughout the season. Such biases may be minimized by high sampling rates (i.e., most every weekday throughout the season) but the temporal pattern of coverage varies from year to year and by region. There is little indication that the survey season was cut short by attainment of the quota. Only West PEI showed a lower sampling density during the last week of the study period. Ideally, surveys would have been conducted daily or randomly within the potential spawning period of herring.

The length of the 28-day period is supported by the spawning event study on Fisherman's Bank (Cairns et al. 1996) and average length of recent fishing seasons. Biases may occur if the start date of the fishery is offset from major waves of spawning activity or if major spawning waves occur after the study period. Given the general absence of trends in the nightly biomass values, we are unable to comment on whether the study period encompasses the majority of spawning activity within each region. A strong economic argument could be made that the fishery depends on a fishing season that is timed with spawning activity, and after 28 days fishing activity has generally tapered to low levels.

SPATIAL-TEMPORAL MODEL

The spatial-temporal model was developed to identify local spawning aggregations as a precursor to assessing fish which are present in aggregations over multiple days (i.e., double-counting). The spawning behaviour assumptions in the model are justified in Fisherman's Bank (Cairns et al. 1993, 1996), however these biological assumptions have not been independently confirmed.

For a modelling perspective, spawning events in Escuminac, West PEI and Fisherman's Bank have similar spatial extents and residence times (Table 2). As a consequence, the relative scaling between the observations and the estimated seasonal biomass is expected to be similar. The spatial extent between spawning event aggregations in Fisherman's Bank of 0.53 km (or 1.06 km at two standard deviations) are consistent with previous estimates of spawning bed size, 0.92 (+/- 0.65) km^2 (Cairns et al. 1996). Cairns et al. (1993, 1996) also found that the observed number of spawning beds per season was between 1 and 7 from 1985 to 1995 on Fisherman's Bank. These values are consistent with our annual average of 3.7 spawning events over the 28 day estimation period. West PEI and Escuminac produced results that were within the expectations from model assumptions.

In Miscou, the model was deemed inconsistent with biological knowledge as the fitted parameters implied long, protracted spawning events spanning large spatial areas. As a consequence, seasonal estimates were essentially the sum of recruitment days over each 28 day sampling season. The distribution of sampling and fishing effort at Miscou shows little clustering of fishing aggregations, which are otherwise present in other regions (Fig. 4). The presence of such spatial features is assumed by the model. This suggests that spawning aggregations in Miscou may follow different spatial dynamics than in other regions. Miscou also had a lower sampling density than other regions (Fig. 2), so that the seasonal estimates for certain years (e.g., 2007 with no observations, 2010 and 2011 with three observations each) are more a reflection of the hierarchical prior for the mean nightly biomass values rather than actual observations. Furthermore, Miscou landings surpassed nightly biomass estimates more frequently than in other regions. Consequently, the data collected from Miscou do not satisfy the model assumptions.

Pictou fishing locations were spread out along the coast and around Pictou Island (Fig. 4). While this data set is richer, spatial clusters and therefore spawning aggregations, were found to be of short duration resulting in approximately half of the schools being classified as roaming, non-spawning fish. These in turn were not considered in the biomass summation, implying that the downward scaling between observed nightly biomass and seasonal biomass was more severe in Pictou than in other areas. Whether this is due to true differences in herring reproductive behaviour, or that the sampling fish harvester is simply more apt to change locations over such a wide area, remains unclear.

These results suggest that seasonal biomass estimates for Miscou and Pictou are not on the same scale as other regions. The model does not appear to produce valid results in these regions.

Given the inconsistencies in model performance and the underlying issues with the data, this project could not be used to develop a time series of local abundance indices for herring as part of the fall herring stock assessment.

SUMMARY AND RECOMMENDATIONS

Summary of results

- Results for Fisherman's Bank, Escuminac, and West PEI are comparable. Seasonal biomass estimates are comparable if sampling methods and biological processes are also comparable.
- Results for Miscou and Pictou spawning components indicate a mismatch between model output and known spawning biology and behaviour.

Recommendations for future analyses

- Possible biases in nightly biomass estimates need to be assessed.
- Observed aggregations need to be well covered by the sampling vessel to ensure edges of observed schools are well defined in the available acoustic data sets, and determine if spatial structure of available data shows evidence of partial coverage or differences between years or regions.
- Some effort must be made to verify that there are no other spawning aggregations in the area which are unaccounted for. The existence of such unobserved aggregations might be inferred from local fleet dynamics, i.e., logbooks or VMS data.
- Uncertainty in the seasonal biomass is in large part driven by variability in observations. An experiment could be conducted where the sampling vessel is active over as many nights as possible over the season. This data set could then be used to test the robustness of the model at varying proportions of missing observations.
- Nightly spawning aggregations may be better characterized by multiple rather than a single coordinate point, to account for more complex local spatial distributions such as when multiple schools are present in an area.

Recommendations for improving the data collection protocols

- Develop clear protocols for ensuring that fishing surveys are complete and that a method for evaluating this completeness is identified.
- Two possibilities for obtaining these data are noting fishing location in logbooks and by VMS recording.

- This protocol will include comments on the number of vessels required and fishery reporting that includes location of catch.
- Strict adherence to protocols in particular that acoustic surveys should be completed prior to conducting the nightly fishing activity.
- Periodic structured surveys might be undertaken over the entire potential spawning area during the spawning season. It is recommended that it be performed once a week on each spawning bed during weekend fishery closures, and also one week prior and two weeks after end of fishing season, assuming a seven day turnover rate.

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TABLES

Table 1. The number and mean surface area of spawning beds detected from Fisherman's Bank spawning bed surveys (Cairns et al. 1996).

Year	Number	Area (km²)
1985	5	0.36
1986	1	1.10
1987	4	0.52
1988	4	0.84
1989	5	0.81
1990	7	0.70
1991	5	1.08
1992	4	1.44
1993	5	1.22
1994	6	1.26
1995	2	0.64

Table 2. Posterior means (95% credibility intervals in parentheses) for selected nightly biomass and spatial-temporal model parameters.

Region	ϕ	σ_0	σ_1	π_0	π_1
Escuminac	0.24 (-0.16 ,0.66)	0.98 (0.85 ,1.12)	16.08 (12.93 ,20.06)	0.87 (0.81 ,0.93)	0.45 (0.27 ,0.65)
Fisherman's Bank	0.01 (-0.44 ,0.49)	0.53 (0.41 ,0.68)	4.39 (3.6 ,5.45)	0.81 (0.71 ,0.9)	0.52 (0.31 ,0.74)
Miscou	0.61 (0.25 ,0.85)	1.46 (1.29 ,1.65)	24.0 (16.45 ,36.27)	0.97 (0.94 ,0.99)	0.48 (0.16 ,0.86)
Pictou	0.48 (0.1 ,0.76)	0.86 (0.66 ,1.12)	8.32 (7.28 ,9.53)	0.55 (0.39 ,0.7)	0.41 (0.26 ,0.58)
West PEI	0.45 (-0.07 ,0.79)	0.68 (0.56 ,0.83)	13.67 (10.59 ,18.2)	0.88 (0.82 ,0.93)	0.65 (0.45 ,0.85)

Table 3. Estimated number (standard error in parentheses) of spawning events for each spawning region by year.

Year	Miscou	Escuminac	West PEI	Fisherman's Bank	Pictou
2002	2.5 (0.7)	3.0 (1.0)	3.2 (1.1)	2.6 (0.8)	3.8 (1.1)
2003	1.1 (0.2)	3.9 (0.5)	2.7 (0.8)	3.7 (1.0)	3.9 (1.0)
2004	1.6 (0.7)	1.6 (0.7)	4.3 (0.5)	3.5 (0.9)	4.2 (1.1)
2005	1.1 (0.3)	3.7 (0.7)	2.5 (1.0)	3.1 (1.1)	3.2 (0.9)
2006	1.0 (0.1)	3.2 (0.8)	3.0 (0.2)	4.1 (1.0)	3.7 (1.0)
2007	1.1 (0.3)	1.4 (0.6)	2.9 (1.0)	4.3 (0.9)	3.3 (1.0)
2008	2.0 (0.3)	3.7 (0.7)	4.1 (0.9)	3.8 (0.8)	4.2 (1.0)
2009	1.0 (0.2)	3.5 (0.6)	3.8 (0.5)	4.1 (1.0)	4.4 (1.0)
2010	1.3 (0.5)	3.5 (0.8)	2.4 (0.6)	3.4 (1.0)	3.9 (1.2)
2011	2.0 (0.3)	4.0 (0.7)	3.0 (0.9)	4.0 (0.9)	3.4 (0.7)
2012	2.3 (0.6)	2.7 (0.7)	3.2 (0.8)	4.0 (1.0)	4.2 (1.1)

FIGURES

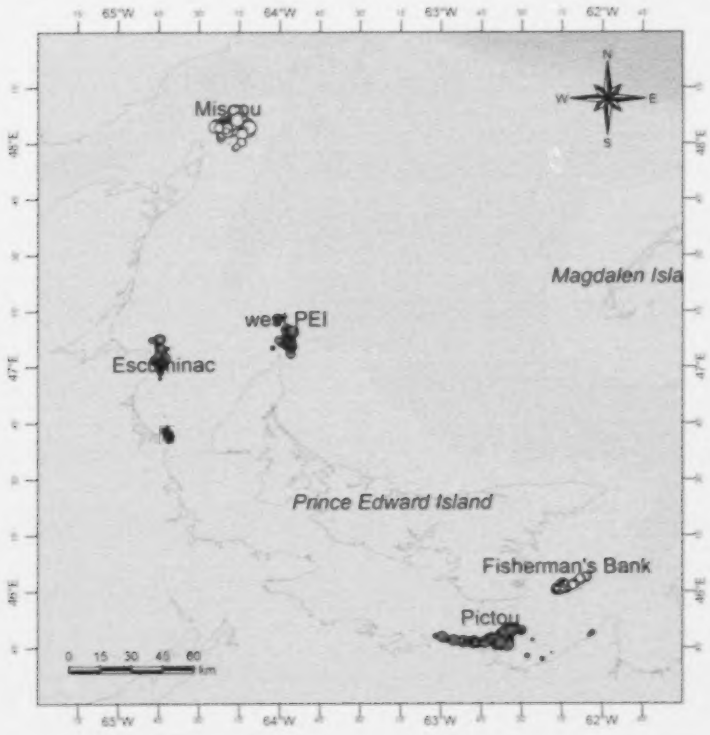

Figure 1. Herring fall spawning locations in NAFO 4T.

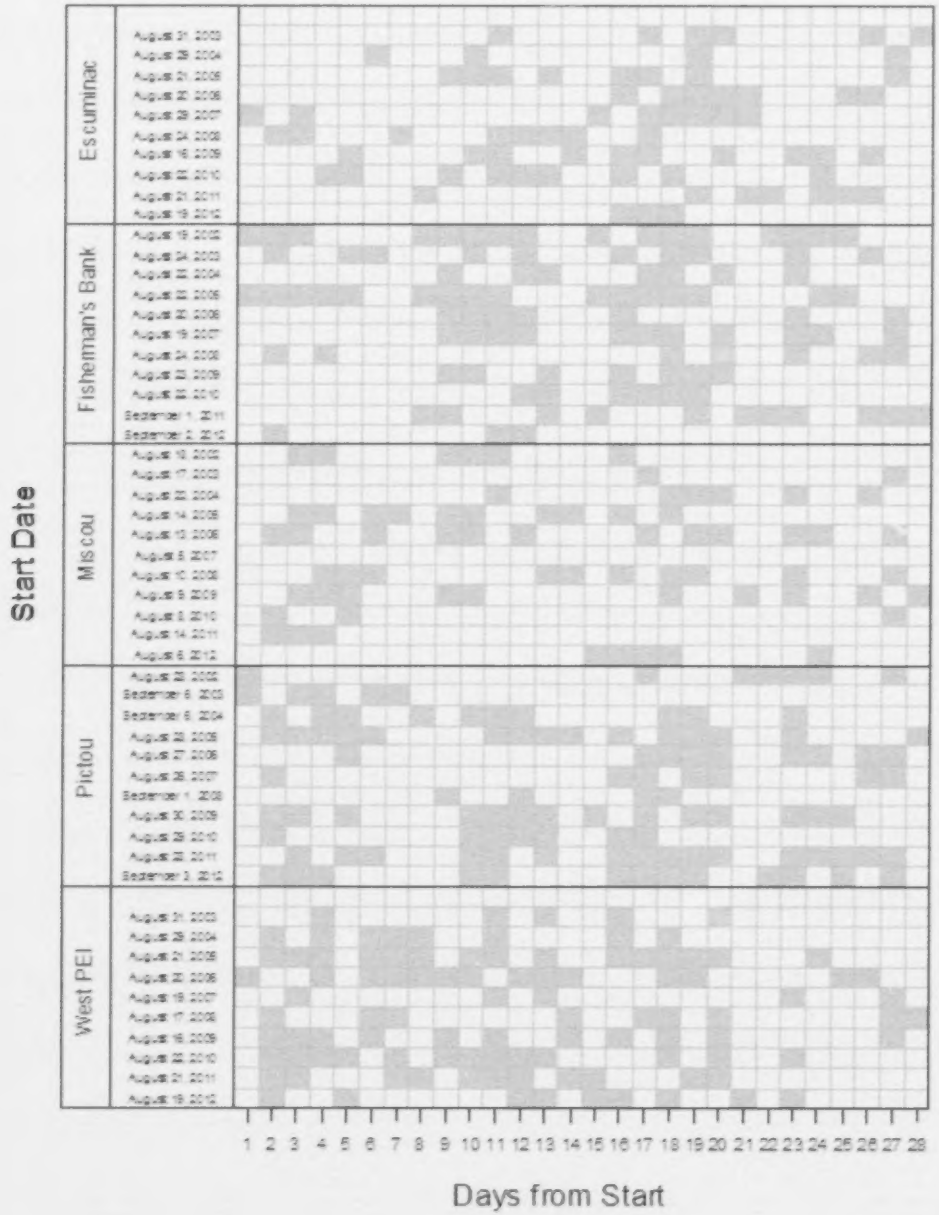
Escuminac
Fisherman's Bank
Miscou
Pictou
West PEI
Start Date
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
Days from Start

Figure 2. Seasonal pattern of nightly observations (grey squares) used for the analysis for each 28-day period by year and spawning region.

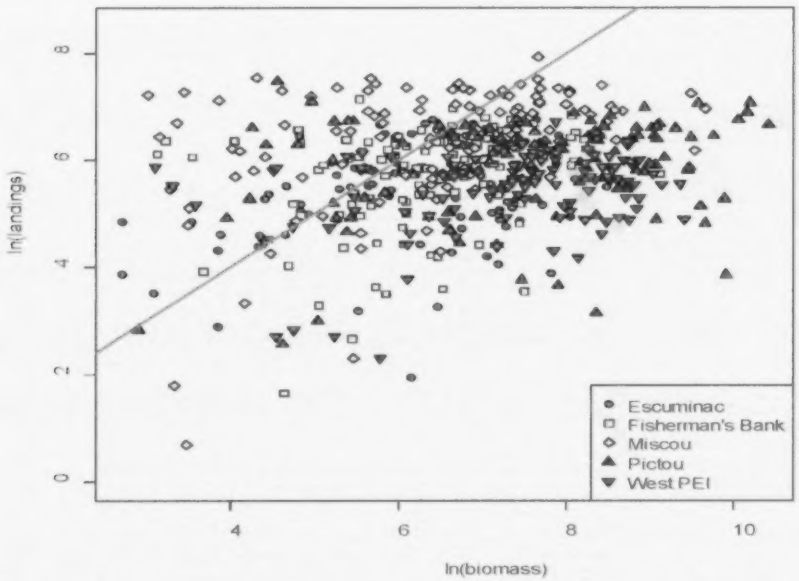

Figure 3. Nightly landings versus nightly biomass estimates for each spawning region for all years combined on the log-scale. The red line is the boundary where nightly landings equal nightly biomass estimates. For points above the line, the nighty landings are greater than the nightly biomass estimates and for points below the line the nightly landings are less than the nightly biomass estimates.

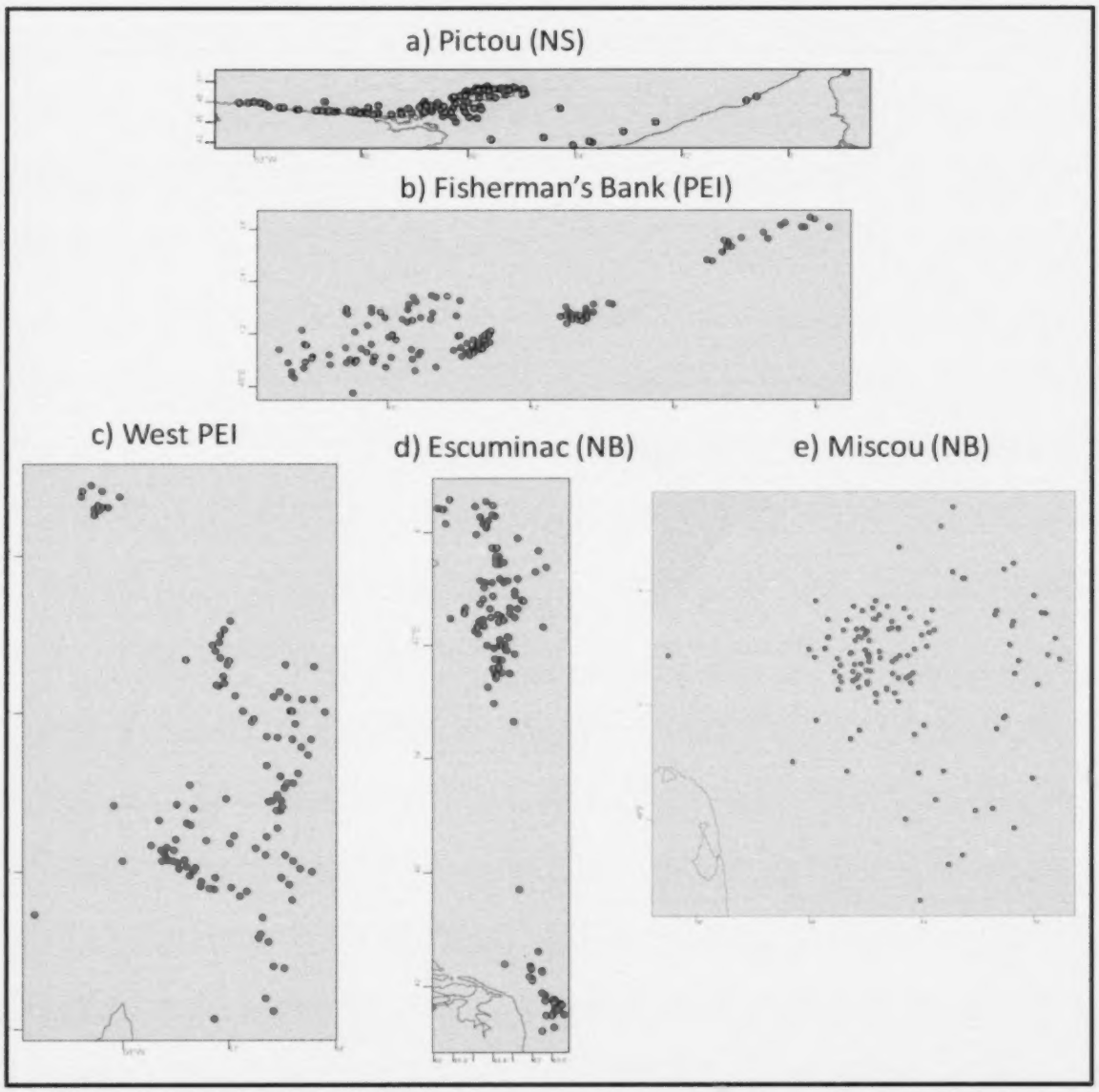

Figure 4. Distribution maps of estimated nightly school locations for each spawning area for all years combined.

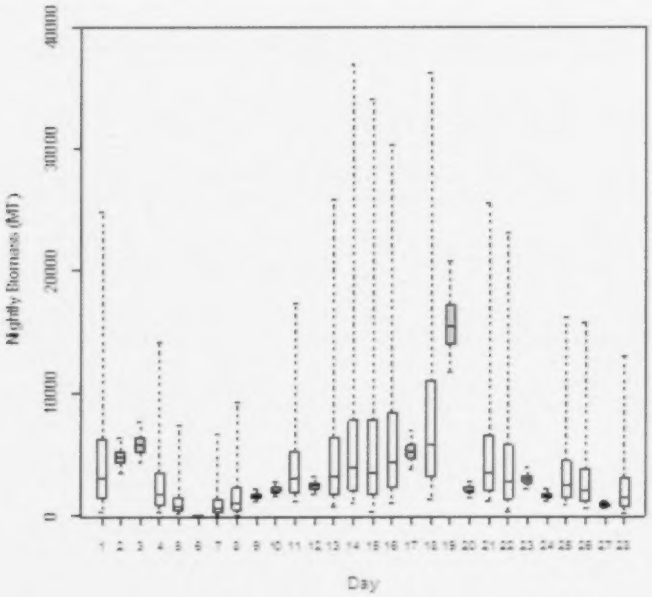

Figure 5. Boxplot of posterior MCMC simulated nightly biomass observations (in grey) and missing values (in white) for Miscou in 2006. Boxplots indicate the median, interquartile range (box) and 95% credibility intervals (whiskers).

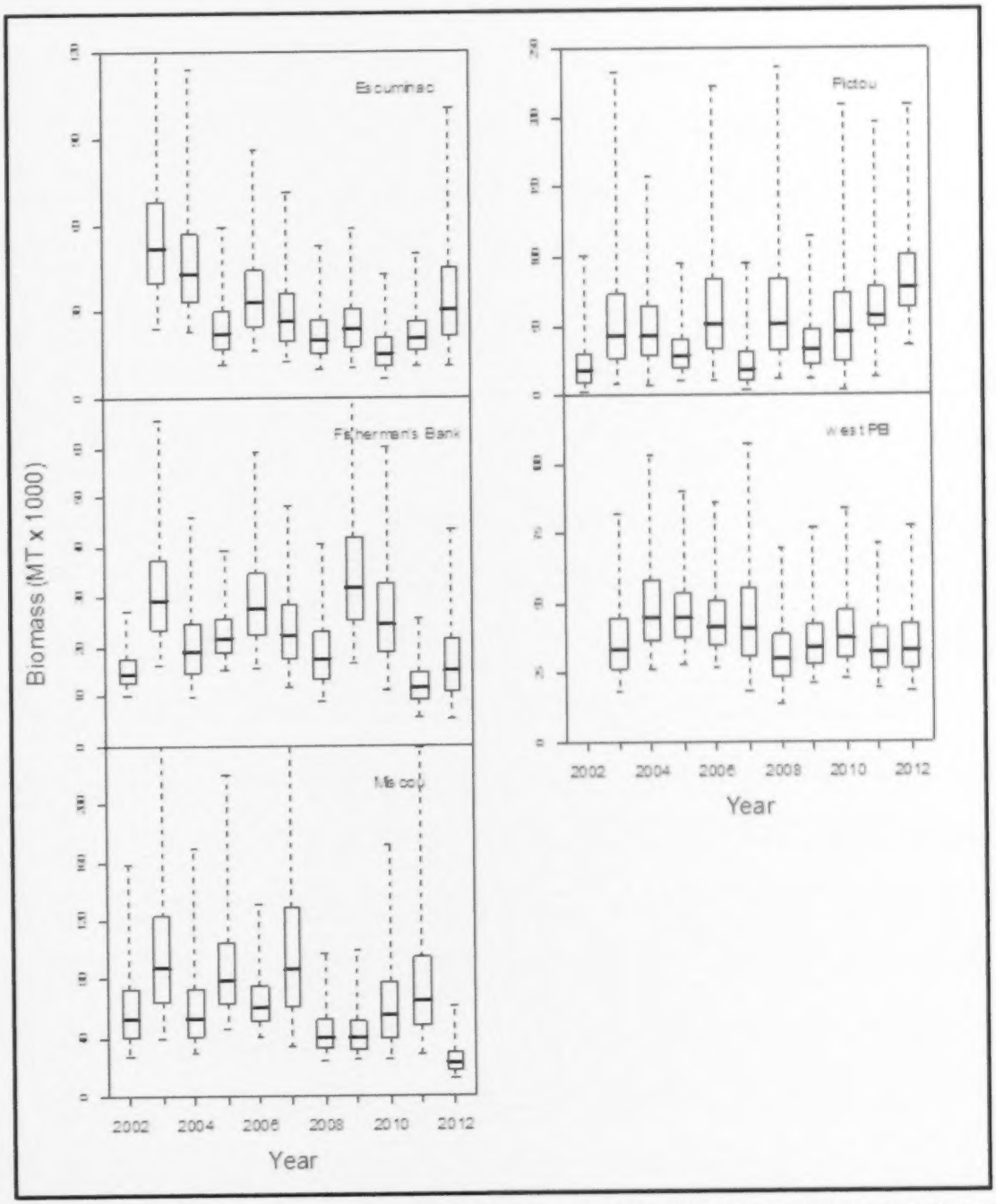

Figure 6. Seasonal biomass estimates by year obtained from MCMC posterior simulations (n = 5,000) for the five spawning areas. Boxplots indicate the median, interquartile range (box) and 95% credibility intervals (whiskers).

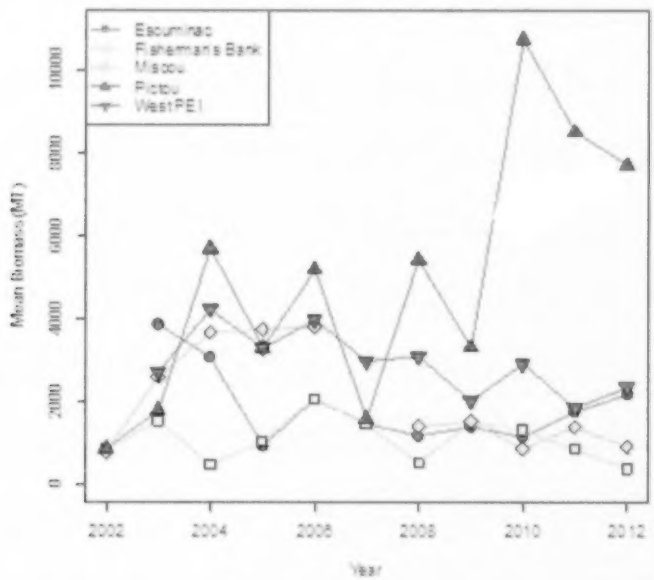

Figure 7. Mean observed nightly biomass for each spawning area by year.

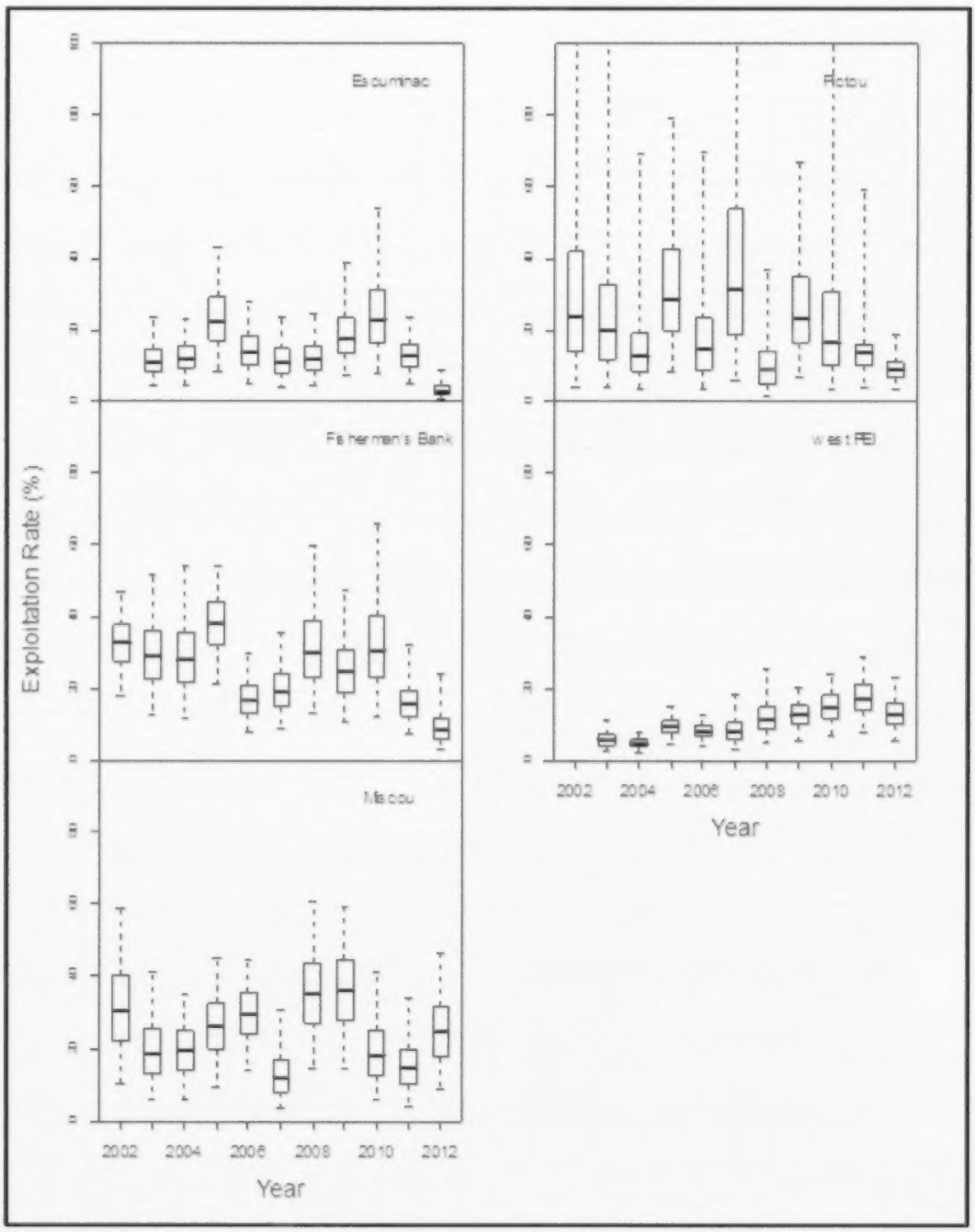

Figure 8. Exploitation rates by year obtained from MCMC posterior simulations (n = 5,000) for the five spawning areas. Boxplots indicate the median, interquartile range (box) and 95% credibility intervals (whiskers).

APPENDICES

APPENDIX A. OPENBUGS CODE FOR THE NIGHTLY BIOMASS MODEL.

```
# Prior over zero proportions:
alpha.pi ~ dexp(1)
beta.pi ~ dexp(1)
for (i in 1:n.region){
    for (j in 1:n.year){
        pi[i,j] ~ dbeta(alpha.pi, beta.pi) } }
# Hierarchical mean prior
mu.mu ~ dnorm(0, 0.01)
tau.mu ~ dgamma(0.1, 0.1)
sigma.mu <- pow(tau.mu, -2)
for (i in 1:n.region){
        phi[i] ~ dunif(-1,1)
        tau.eps[i] ~ dgamma(1,1)
        tau.eps.global[i] <- (1-pow(phi[i], 2)) * tau.eps[i] }
for (i in 1:n.region){
    for (j in 1:n.year){
        mu.year[i,j] ~ dnorm(mu.mu, tau.mu)
        eps[i,j,1] ~ dnorm(0, tau.eps.global[i])
        for (k in 2:n.day){
        mu.eps[i,j,k] <- phi[i] * eps[i,j,k-1]
        eps[i,j,k] ~ dnorm(mu.eps[i,j,k], tau.eps[i]) }
        for (k in 1:n.day){
        mu[i,j,k] <- mu.year[i,j] + eps[i,j,k] } } }
# Prior observation error
tau.b ~ dgamma(0.1, 0.1)
var.b <- 1 / tau.b
sigma.b <- sqrt(var.b)
# Additional observation error parameters
cv.mu <- -log(pow(0.15,2) + 1) / 2
cv.tau <- 1 / log(pow(0.15,2) + 1)
# Observation error model
for (i in 1:n){
        b[i]  ~ dlnorm(mu[region[i], year[i], day[i]], tau.b) I(L[i], )
        z[i]  ~ dbern(pi[region[i], year[i]])
        cv[i] ~ dlnorm(cv.mu, cv.tau)
        biomass[day[i], year[i], region[i]] <- (1-z[i]) * b[i] * cv[i] }
```

APPENDIX B. OPENBUGS CODE FOR THE SPATIAL-TEMPORAL CLUSTERING MODEL.

```
# Prior over transition probabilities
for (i in 1:2){
        alpha.p[i] ~ dexp(1)
        beta.p[i] ~ dexp(1)
    for (k in 1:n.region){
        P[k,i] ~ dbeta(alpha.p[i], beta.p[i]) } }
# Define Markov probability transition matrix
for (k in 1:n.region){
        T[k,1,1] <- P[k,1]
        T[k,1,2] <- 1 - P[k,1]
        T[k,2,1] <- P[k,2]
        T[k,2,2] <- 1 - P[k,2]}
# Define state of initial distance observation
for (j in 1:n.year){
    for (k in 1:n.region){
        S[1,j,k] <- 1
        C[1,j,k] <- 1 } }
# Define the Markovian state vector of observations
for (i in 2:n.day){
    for (j in 1:n.year){
        for (k in 1:n.region){
        S[i,j,k] ~ dcat(T[k, S[i-1,j,k],1:2])
        C[i,j,k] <- C[i-1,j,k] + (S[i,j,k]-1) } } }
# Spatial extent of spawning event
for (m in 1:2){
        alpha.tau[m] ~ dexp(1)
        beta.tau[m] ~ dexp(1)
    for (k in 1:n.region){
        tau[k,m] ~ dgamma(alpha.tau[m], beta.tau[m])
        sigma[k,m] <- pow(tau[k,m], -0.5) } }
# Coordinate random walk
for (j in 1:n.year){
    for (k in 1:n.region){
        x[(j-1)*n.day*n.region + (k-1)*n.day + 1] ~ dnorm(0, 0.001)
        y[(j-1)*n.day*n.region + (k-1)*n.day + 1] ~ dnorm(0, 0.001) } }
for (i in 2:n.day){
    for (j in 1:n.year){
        for (k in 1:n.region){
        x[(j-1)*n.day*n.region + (k-1)*n.day + i] ~
        dnorm(x[(j-1)*n.day*n.region + (k-1)*n.day + i - 1], tau[k,S[i,j,k]])
        y[(j-1)*n.day*n.region + (k-1)*n.day + i] ~
        dnorm(y[(j-1)*n.day*n.region + (k-1)*n.day + i - 1], tau[k,S[i,j,k]]) } } }
```